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Modelling and Control of Wind-PV Based Hybrid Power System Considering Hybrid Energy Storage System Incorporating Battery and Supercapacitor

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ABSTRACT

In this paper a control strategy is proposed for the control of battery-supercapacitor based hybrid energy storage system applied to wind-PV based hybrid renewable energy system. The hybrid combination of battery-supercapacitor provide complement solution for high power and higher energy storage system and thereby covering wide range of applications. The controller is designed based on the variations in the DC link voltage and these variations are suppressed using controller. The proposed controller is tested under two modes of operations: surplus power mode and deficit power mode. The power imbalance between supply and demand is minimized using hybrid energy storage system where low frequency components are absorbed by battery and high frequency components are tackeld by supercapacitor. The results show that the proposed control strategy worked satisfactorily for both the case. The results are verified in MATLB/Simulink environment.

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1. INTRODUCTION

The proliferation of renewable energy resources (RERs) based electricity generation in recent years can be attributed to the depleting fossil fuels and their adverse impact on the environment besides the exponentially increasing electricity demand. Apart from this, the RERs are sustainable in nature and ecofriendly [1, 2]. But the intermittent and random nature of RERs by way of being weather dependent is a cause of concern and consequently the reliability of the RERs based energy systems is on lower side. In the recent times, hybrid renewable energy systems (HRESs), comprising two or more different RERs and energy storage systems (ESSs), have emerged to be a promising technology and have got huge potential to fulfill electricity demands of remote regions especially where grid access is not available. Keeping in view these observations and to make the reader better understand the perspective, a novel control strategy is proposed for a grid-independent wind-PV based HRES with built-in HESS- battery-supercapacitor configuration- with the following objectives:

1. Active power balance among different components of HRES.
2. DC link voltage (V_{DC}) regulation irrespective of change in wind speed, solar irradiation and the load connected to the AC bus.
3. Power sharing between BESS and SCESS in such a way that BESS has to counter only the low frequency components and SCESS the high frequency components of power imbalance and thereby reducing the stress on BESS.
4. Meeting the SoC constraints of HESS while maintain the power balance.

2. System Description

The grid-independent HRES, considered for investigation and as shown in Fig. 1, comprises RERs-WECS and PV system, HESS-BESS and SCESS, DC dump load, and the AC load- both critical and non-critical, connected in the system through their respective controlled power electronic converters. The PV system and the WECS, after conversion of AC output power into DC using diode rectifier, are connected to the DC link capacitor through DC-DC boost converters, both BESS and SCESS are connected to the DC link capacitor through DC-DC buck-boost converters, whereas, the DC-DC buck converter is used to connect the dump load. The DC bus (directly connected to the DC link capacitor), through three-phase voltage source inverter (VSI), is interconnected with the AC bus where AC load is connected. To extract maximum power, the maximum power point tracking (MPPT) systems are employed on both WECS and the PV system, respectively. BESS, as the main storage system, injects power into the system when the power generated by HRES is not sufficient to meet the load demand and absorbs power from the system whenever the power generated by HRES is in excess [3, 4]. BESS, while has high reliability on one hand, suffers on account of slow response during transient conditions, on the other hand. Consequently, SCESS is employed to compensate for the slow dynamics of BESS. The dump load gets connected to the DC bus only when excess power is available from RERs and the BESS is in full charged state. The critical load has to be served at all times anyway, irrespective of the operating conditions while maintaining the terminal voltage and frequency within limits for smooth operation, whereas there the non-critical load is free from any such constraints. The various technical specifications of the constituents of HRES have been provided in Appendices I-IV.

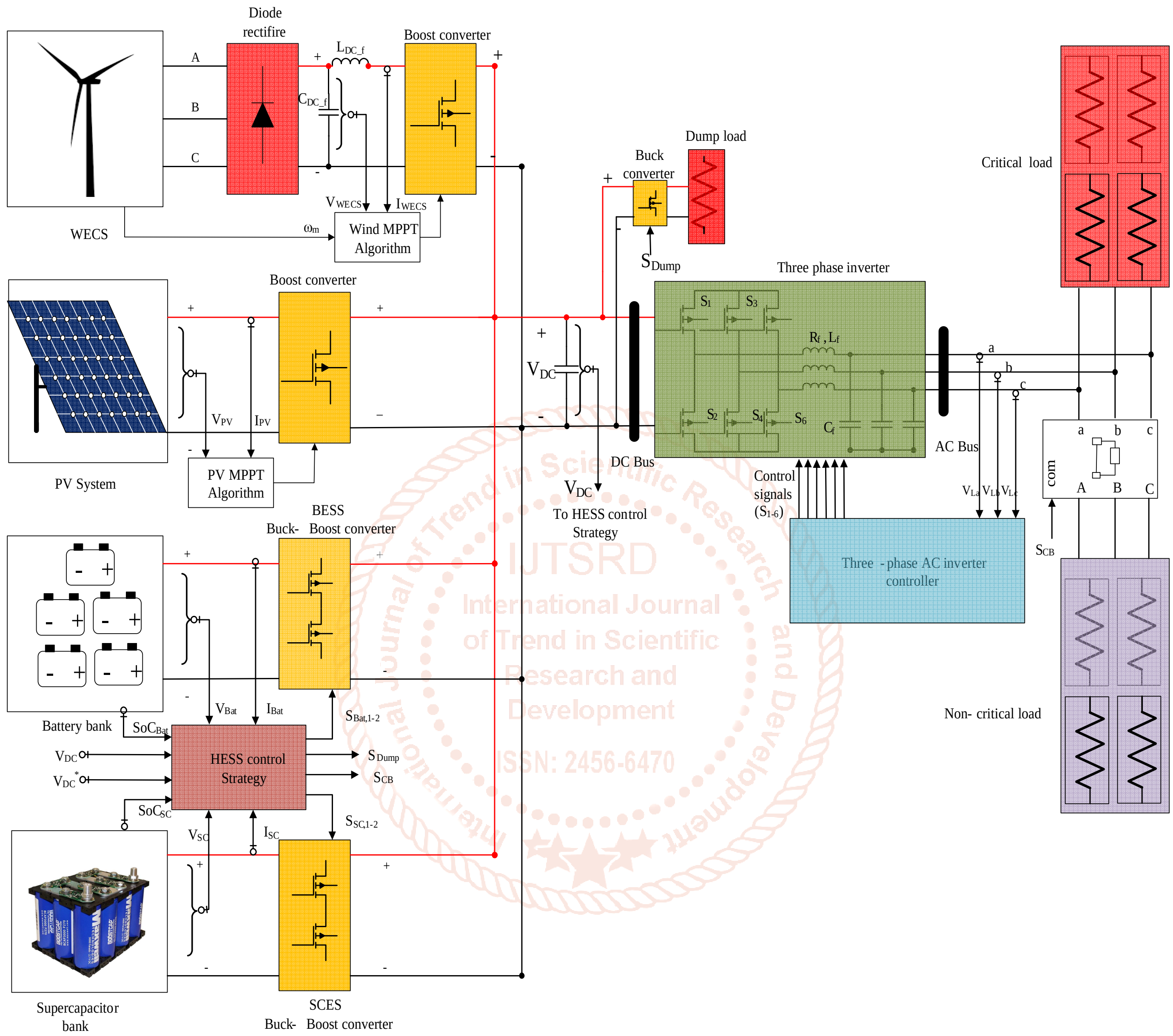

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Fig. 1 Schematic of HRES

3. Control Strategy for Hybrid Renewable Energy System

Due to weather dependency of the RERs in the HRES and also the load being variable, power imbalance between generation and consumption always exits and thereby causing the V_{DC} to fluctuate. Therefore, the need for some suitable control strategy to be in place so as to maintain power balance and also to regulate the V_{DC}, terminal voltage and frequency around the normal values within prescribed limits under all operating conditions. The control strategy proposed here is so designed as to attain these objectives in two parts: HESS control and AC side inverter control. The control strategy is realized through various power converters (DC/DC converters for BESS, SCESS, WECS, PV system, and dump load and DC/AC inverter for interfacing DC and AC bus) interfaced with various components of HRES and data collection and measurement units. [13,14]

3.1 HESS control strategy

The proposed control strategy for HESS involves the decision making process to decide the operating modes of the system based on the situation whether the power is in surplus or in deficit. The objectives of the strategy include:

- Regulating the DC link voltage within stiff limits.
- Maintaining the active power balance between generation and consumption by charging/discharging the HESS, giving excess power to dump load, and load shedding of non-critical load.
- Diverting the fast transients of active power mismatch to the SCESS (> 0.5 Hz.) and slow transients to BESS (< 0.5 Hz.)

- Maintaining always the SoC constraints for HESS, which is specified as $0.2 \leq SoC_{Bat} \leq 0.8$ and $0 \leq SoC_{SC} \leq 1$ for BESS and SCESS, respectively.

Following are the two modes of this strategy based on the available output powers of WECS and PV system both combined and the connected load:
The power balance equation in HRES, as shown in Fig. 1, at DC bus is given as follows:

$$P_{PV} + P_{WECS} - P_{Load} - P_{Loss} = \pm P_{Bat} \pm P_{SC} \qquad (1)$$

As can be made out from Fig. 3, when the BESS is operating within its SoC limits, the error between the actual V_{DC} and reference V_{DC}^* acts as input to proportional-integral (PI) controller whose output is the I_{DC}^* for the HESS. The I_{DC}^* then goes as input to the LPF which filters out, as a function of LPF ($f_{LPF}(1)$) as given by equation (2), the low frequency components ($I_{L\_freq}^*$) from I_{DC}^*:

$$I_{L\_freq}^* = f_{LPF}(I_{DC}^*) \qquad (2)$$

$I_{L\_freq}^*$ is then processed through the rate-limiter so as to obtain the reference current for BESS (I_{Bat}^*) as a function of rate-limiter ($f_{RL}(□)$) that decides its charge/discharge rate as given in equation (3):

$$I_{Bat}^* = f_{RL}(I_{L\_freq}^*) \qquad (3)$$

Another PI controller is employed to compensate the error (I_{B_err}) between I_{Bat}^* and measured battery current (I_{Bat}). The duty ratio (D_{Bat}), obtained as an output of this PI controller,
goes to pulse width modulation (PWM) generator to generate the switching signals ($S_{Bat,1-2}$) for the DC/DC converter of the BESS.

By subtracting the $I_{L\_freq}^*$ from I_{DC}^*, high frequency components ($I_{H\_freq}^*$) are separated as given in equation (4).

$$I_{H\_freq}^* = I_{DC}^* - I_{L\_freq}^* \qquad (4)$$

Given the slow dynamics of BESS, the BESS cannot follow I_{Bat}^* instantly, consequently, uncompensated power (P_{B_uncomp}), as computed in equation (5), is compensated by SCESS basis the reference current for SCESS (I_{SC}^*), as in equation (6).

$$P_{B\_uncomp} = \left(I_{H\_freq}^* + I_{B\_err}\right) \times V_{Bat} \qquad (5)$$

$$I_{SC}^* = \frac{P_{B\_uncomp}}{V_{SC}} = \left(I_{H\_freq}^* + I_{B\_err}\right) \times \frac{V_{Bat}}{V_{SC}} \qquad (6)$$

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Where,
V_{Bat} and V_{SC} are the terminal voltages of BESS and SCESS, respectively.

3.2 AC side inverter controller

The AC side three phase inverter controller, shown in Fig. 4, provides suitable switching signals to the three phase inverter, the interface between DC bus and AC bus, in a way to ensure that the voltage and frequency are regulated around the nominal values at the AC bus.

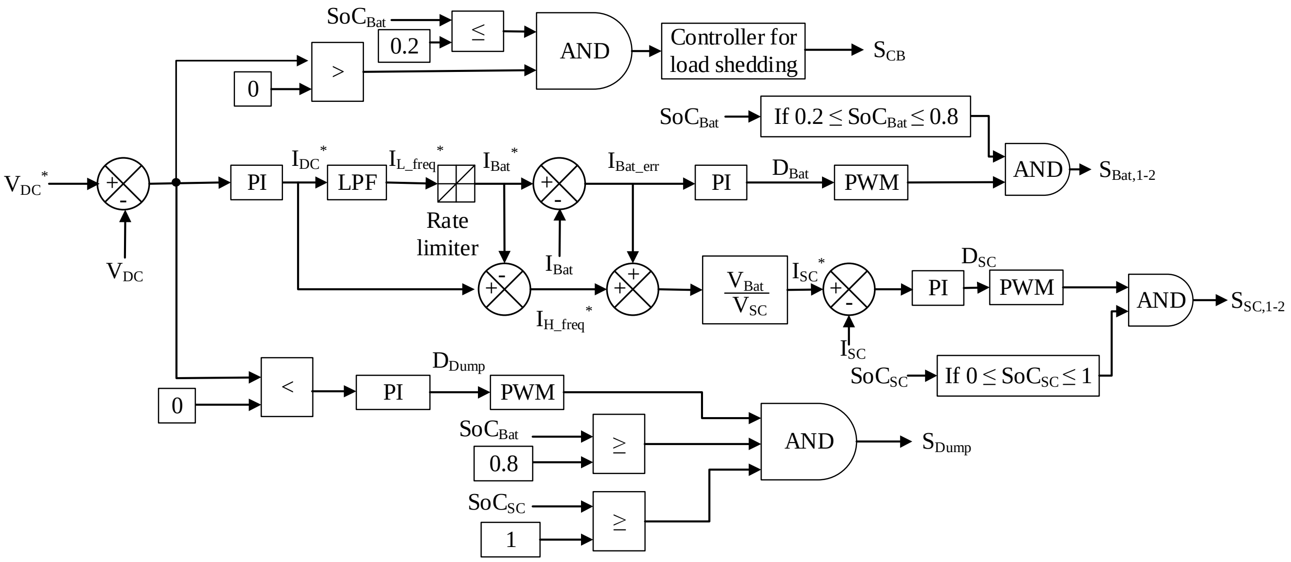

Fig. 3 HESS control strategy

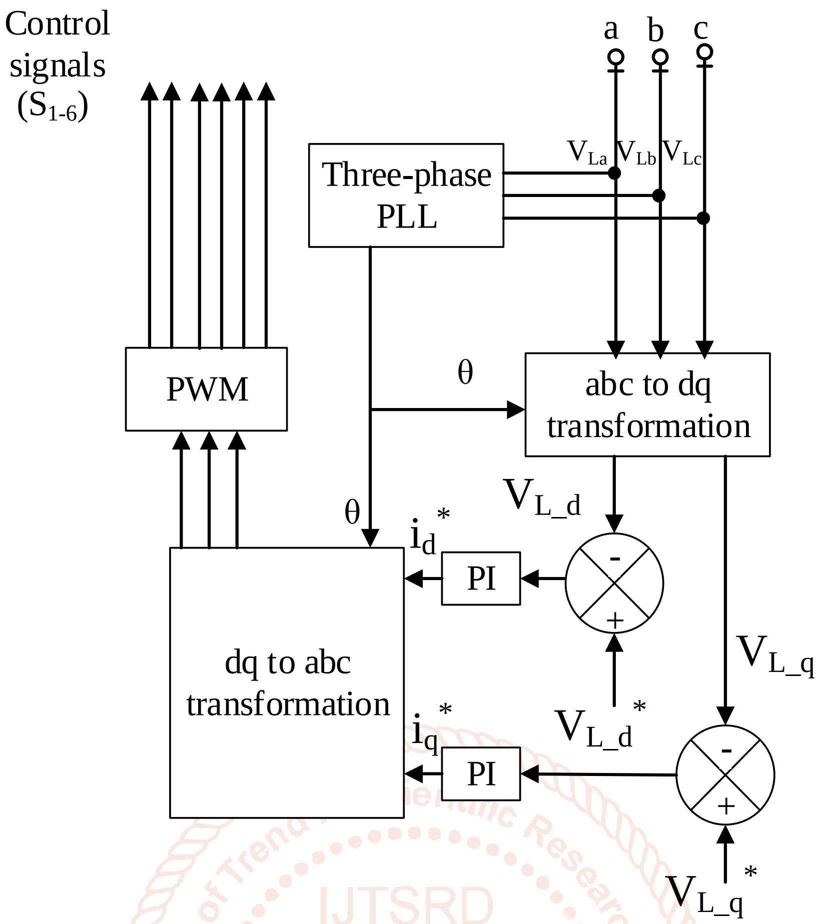

Fig. 4 Three phase inverter controller

4. Simulation results and discussion

The grid-independent HRES, considered for study and as shown in Fig. 1, is modelled and simulated in MATLAB/Simulink with the proposed control strategy and various simulation parameters are presented in Table 2. As the generated power of the HRES at any instant of time is going to be either more or less than the load demand, therefore, simulations are carried out for both the operating modes: the SPM and the DPM and the results are discussed as such.

4.1 Surplus power mode (SPM)

In this mode, the generated power is more than the consumption and hence this surplus power is first utilized to charge the BESS and SCESS and once the SoC_{Bat} attains the upper limit of 80%, then the still excess power is transferred to the dump load for maintaining active power balance. Given the unpredictable nature of the RERs coupled with the varying load demands, the system performance is studied under the varying operating conditions to have a realistic assessment.

The variability of generated powers of the WECS and PV system as per the variations in wind speed and solar irradiance, respectively are shown in Fig. 6 (g). The surplus power of HRES is utilized for the purpose of charging the HESS, with low frequency components of the surplus power being used for the BESS, whose current variation is shown in Fig. 6 (b), which follows the varying operating conditions. The high frequency components of the surplus power, on the other hand, are diverted to the SCESS with its current varying as shown in Fig. 6 (e), which is also in line with the changing operating conditions. When the solar irradiance encounters a step change at t=2 (Fig. 5 (b)), accordingly the PV system current also varies and so does the power, as can be seen in Fig. 6 (a) and Fig. 6 (g), respectively. Because the PV system has got negligible inertia, there is sharp change in PV system current whenever there is a change in solar irradiance, consequently, therefore, resulting in instant change in the output power. This is where SCESS plays its role of compensating for the instant change in the current and output power of the PV system during transients, which is then gradually taken over by BESS and thus protecting the BESS from steep charging as are shown in Fig. 6 (e), Fig. 6 (b), and Fig. 6 (g). At t= 3 s, step increase in wind speed (Fig. 5 (a)) causes WECS current (Fig. 6 (d)) to increase and thereby the power of WECS (Fig. 6 (g)). Now more current is available for charging of BESS and hence it draws more current (Fig. 6 (b)) as well as power (Fig. 6 (g)) at this instant. Again, at t= 4 s, with the solar irradiance getting a step increase (Fig. 5 (b)), the PV system current and power are further increased leading to availability of more surplus power for charging of BESS. At around t= 4.6 s, SoC_{Bat} reaches to its upper limit (80%) which means the BESS can't absorb more power (Fig. 6 (c)) and therefore, the SoC_{Bat} remains constant at 80% thereafter. But surplus power is still available, so, at this instant dump load gets activated and is clearly visible in Fig. 6 (g). At time t=5 s, due to yet another step rise in wind speed, the WECS generates even more power which means even more excess power goes to dump load (Fig. 6 (g)) as BESS is already on its maximum SoC limit. Further, due to the step decrement in load at t= 6 s, more surplus power becomes available leading to increase in power being transferred to the dump load (Fig. 6 (g)). During the entire SPM, the SoC_{SC} remains within the operating limits ($0 \le SoC_{SC} \le 1$) and the SCESS, after absorbing the fast transients at every disturbance, gets back to charging state which is depicted in Fig. 6 (f).

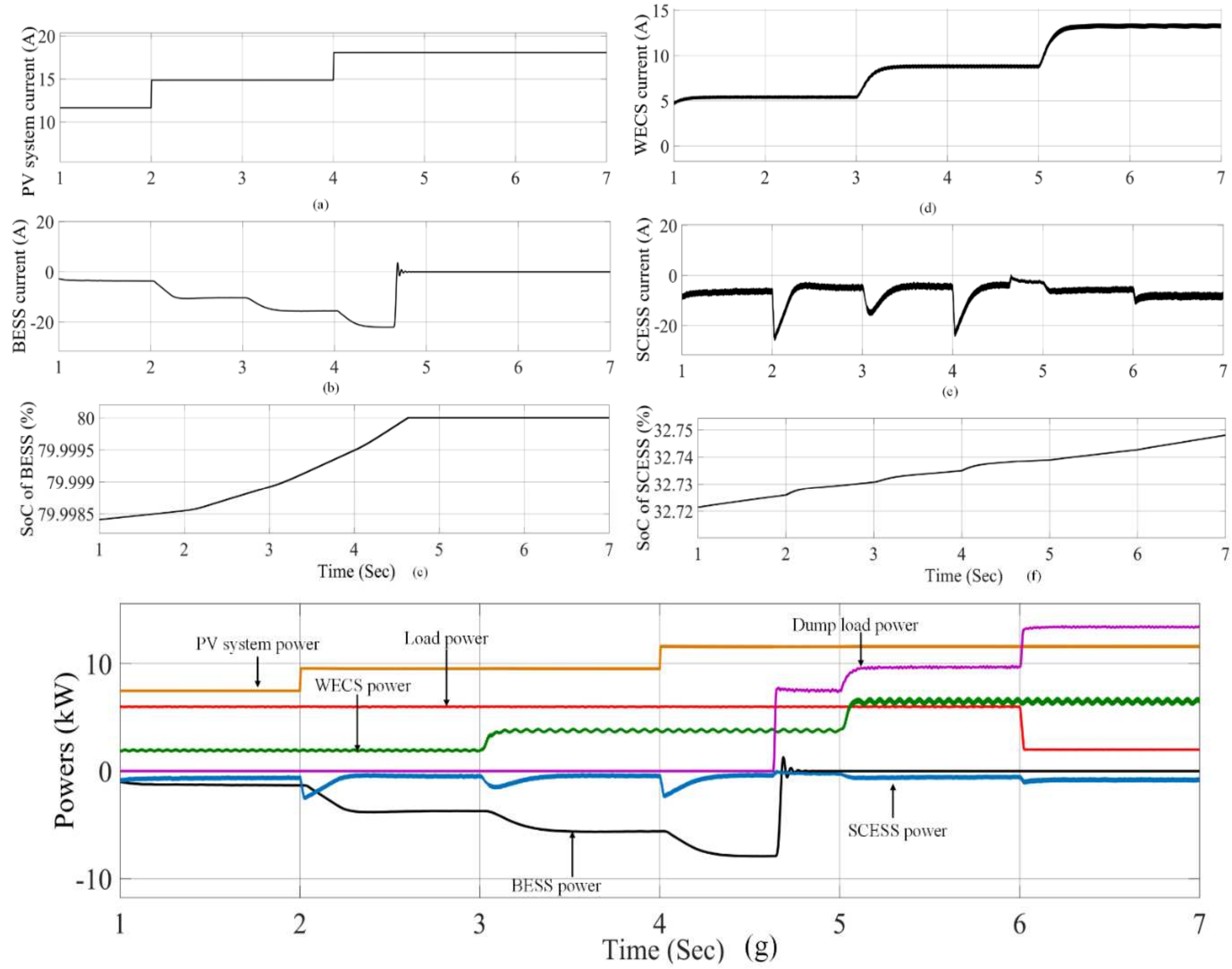

Fig. 6 Simulation results under SPM: (a) PV system output current (A), (b) BESS current (A), (c) SoC_{Bat} (%), (d) WECS output current (A), (e) SCESS current (A), (f) SoC_{SC} (%) and (g) Power sharing among different components (kW)

4.2 Deficit power mode (DPM)

To evaluate the proposed control strategy against the under-generation scenario of HRES, simulations are carried out in DPM. This is where the BESS and SCESS come to the rescue and share the deficit power according to low and high frequency components of power imbalance, respectively. Although the ratings of the HESS are kept such that the SoC_{Bat} never goes below the lower limit (20%) even when the wind and solar power is not available for a longer duration. But, the system is still investigated also for these eventualities which require the non-critical load to be curtailed if the SoC_{Bat} drop below the lower limit which, however, is not allowed to drop. To realize this scenario, the SoC_{Bat} is intentionally taken just over 20%, making the BESS cutoff itself from the system when SoC_{Bat} touches 20% mark. The variations in currents and powers of the proposed system corresponding to the varying operating conditions (wind speed, solar irradiance and load) are shown in Fig. 8. At t= 2 s, when solar irradiance reduces from 1000 W/m^2 to 500 W/m^2 (Fig. 7 (b)), PV system current decreases (Fig. 8 (a)) and so does the power (Fig. 8 (g)). This deficit in power is compensated by HESS by getting discharged according to the control scheme. The BESS compensates for only the low frequency components as can be inferred from the current waveform of BESS (Fig. 8 (b)) and SCESS takes care of the high frequency components as reflected in its current waveform (Fig. 8 (e)). Meanwhile, at t=3 s, when the output current of WECS becomes zero (Fig. 8 (d)) as the wind speed dropping below the cut-in speed of wind turbine (Fig. 7 (a)), the corresponding power of WECS also becomes zero (Fig. 8 (g)). Further, at t=4 s, solar irradiance also becomes zero, consequently making the current and power of the PV system also dropping to zero, as shown in Fig. 8 (a) and Fig. 8 (g), respectively. During t= 4 to 5 s, there is no power available from either the WECS or the PV system and hence the entire load in this duration is served by the BESS after fast transients having been absorbed by SCESS, as is clearly visible in Fig. 8 (b), Fig. 8 (e) and Fig. 8 (g). As wind speed is increased to 12 m/s at t= 5 s (Fig. 7 (a)), meaning thereby the availability of power from WECS, some of the load is also shared by WECS as shown in Fig. 8 (g). During the course of DPM, BESS is in discharging mode with SoC_{Bat} continuously decreasing and eventually reaching to its lower limit (20%) at the instant t= 6.2 s, as depicted in Fig. 8 (b), Fig. 8 (c), and Fig. 8 (g), when the HESS controller isolates the BESS from the system so as to stop it from further discharging and to maintain lower SoC_{Bat} limit. Because of the fairly adequate size of BESS, the SoC_{SC} is always maintained within limits as shown in Fig. 8 (f) by making the SCESS switch to charging just after every discharge to make it ready to compensate for the next transients. As the system is in DPM, no surplus power is available and therefore, the dump load is not activated at any instant (Fig. 8 (g)).

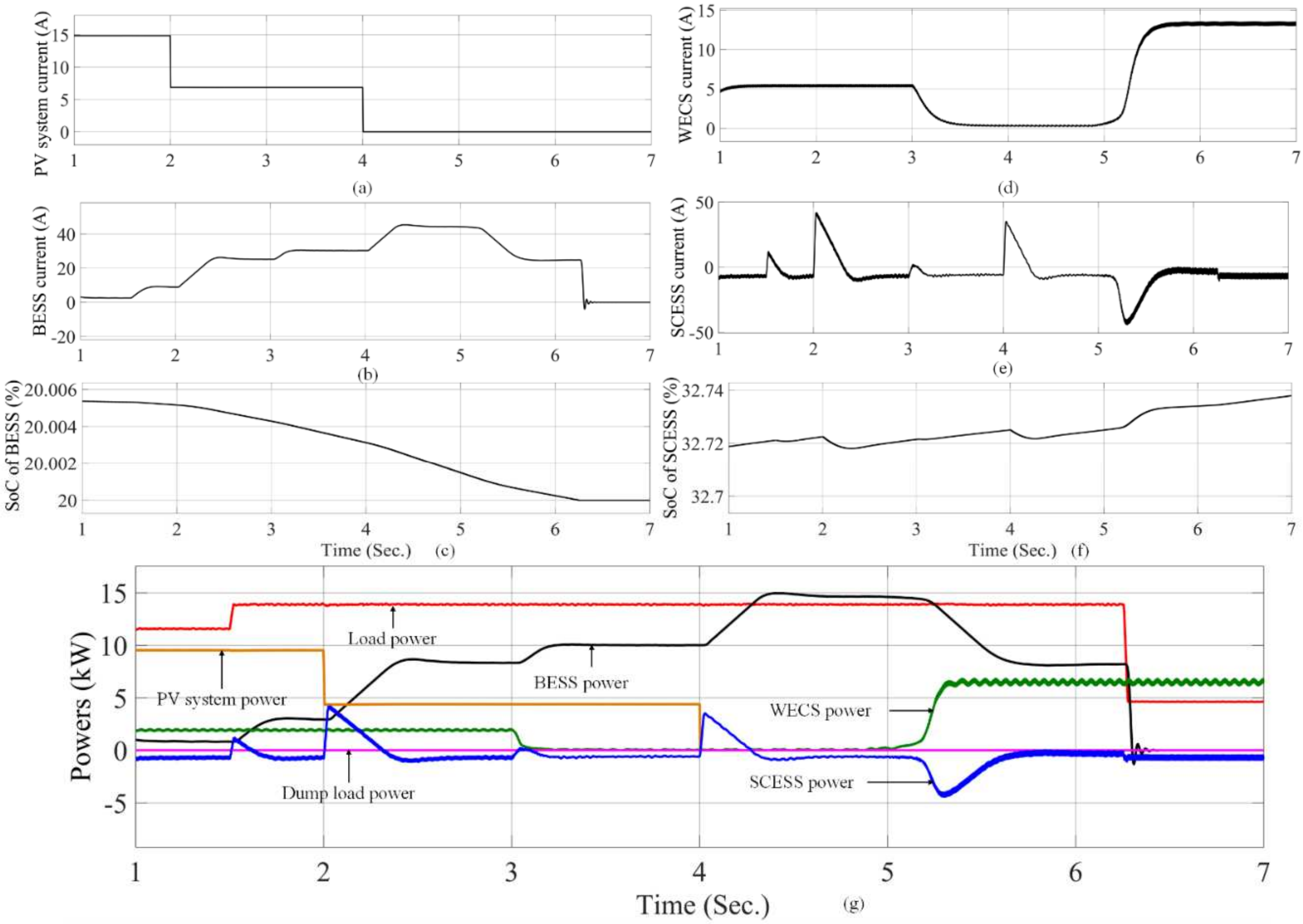

Fig.7 Simulation results under DPM: (a) PV system output current (A), (b) BESS current (A), (c) SoC$_{Bat}$ (%), (d) WECS output current (A), (e) SCESS current (A), (f) SoC$_{SC}$ (%) and (g) Power sharing among different components (kW)

5. Conclusions

A novel control strategy for a grid-independent HRES is proposed with a HESS, consisting of BESS and SCESS. The performance of the control strategy is evaluated by two modes of operation i.e. SPM and DPM of the HRES and performance has been found effective in both the modes. Following are the contributions of proposed control strategy: i) faster voltage regulation, ii) reduced computational burden, iii) less stress on BESS and increased operating life, iv) good power quality at the load end, v) maintenance of SoC constraints of HESS, and vi) stable operation over wide range of operating conditions. The effectiveness of the proposed control strategy is demonstrated by the results obtained from MATLAB as well as validated through HIL OPAL-RT real-time simulator. The proposed control strategy can be further improved in future to be compatible with grid connected mode also.

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